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COMPENSATED AND UNCOMPENSATED NOSE BOOM STATIC PRESSURES MEASURED FROM TWO AIR DATA SYSTEMS ON A SUPERSONIC AIRPLANE

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16. Abstract

Two static-pressure-measuring air data systems that were used on the YF-12 airplane for supersonic flight testing were compared. One system consisted of a nose boom pitot-static probe with two sets of static-pressure orifices designed for static-pressure error compensation, two air data computers, and a photopanel for recording. The other system consisted of an identical nose boom probe and a third set of static-pressure orifices not designed for error compensation, pressure transducers for direct pressure measurements instead of air data computers, and a pulse code modulation system for recording.

The comparisons showed that the uncompensated static-pressure orifices provided more accurate air data measurements than either set of compensated static-pressure sources. Whereas the uncompensated static-pressure source was relatively insensitive to angle of attack, the compensated sources were characterized by a position error at supersonic speeds that increased with angle of attack and Mach number. Pitot-static measurements acquired by using air data computers that incorporate cams for static error compensation provide reference data that are less accurate than similar measurements made by pressure transducers.

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COMPENSATED AND UNCOMPENSATED NOSE BOOM STATIC PRESSURES MEASURED FROM TWO AIR DATA SYSTEMS ON A SUPERSONIC AIRPLANE*

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INTRODUCTION

Modern aircraft often use an aerodynamically compensated pitot-static nose boom probe combined with an air data computer to acquire data for cockpit displays of Mach number, airspeed, and pressure altitude. The static-pressure orifices of these probes are located so that the position error due to the probe compensates for the position error due to the aircraft's forebody. Error is minimized in the transonic speed region, where it is usually large for uncompensated probe installations. The YF-12 airplane (ref. 1), which is being flight tested at the NASA Flight Research Center, is equipped with a compensated pitot-static nose boom probe. A mechanical cam inside the airplane's air data computer further reduces the position error. The cam correction was determined from wind-tunnel tests of the probe as a function of the ratio of the sensed pitot pressure to the pitot-static pressure differential. However, wind-tunnel tests also indicated that at supersonic speeds the position error was significantly affected by flow angularity, for which the air data computer cannot compensate.

The YF-12 compensated probe and air data computer have generally provided satisfactory data for pilot display and aircraft system control. However, the validity of using the data as reference data for aerodynamic research has been questioned because of the effects of flow angularity on the static-pressure measurements. Therefore, for recent flight testing, an uncompensated set of static-pressure orifices was added to the probe in a configuration known to be relatively insensitive to moderate angles of attack. Pressure transducers for the direct measurement of pitot and static pressures were also added. So that precise air data could be obtained from the modified system, calibration flight tests were made to define the position errors of both the compensated and the uncompensated static-pressure sources.

This paper compares the characteristics of the static-pressure measurements from both types of static-pressure sources. The effects of angle of attack on the compensated static-pressure measurements are demonstrated by comparing these measurements with measurements from the uncompensated source. A discussion is included on the laboratory calibrations of the air data computers to illustrate the complexity of determining static-pressure position error when air data computers that make a mechanical correction of static-pressure error are used.

*Title, Unclassified.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. Measurements were taken in U.S. Customary Units. Conversion factors relating the two systems are given in reference 2.

h_p	pressure altitude, geopotential km (ft)
M	free-stream Mach number
M_{S_1}	Mach number calculated from S_1 static-pressure source; includes all known corrections except that for angle of attack
M_{S_2}	Mach number calculated from S_2 static-pressure source; includes all known corrections except that for angle of attack
M_{S_3}	Mach number calculated from S_3 static-pressure source
p	static pressure, kN/m^2 (psi)
p_t	pitot pressure, kN/m^2 (psi)
S_1, S_2	compensated static-pressure sources
S_3	uncompensated static-pressure source
t	time, sec
V_e	equivalent airspeed, m/sec (knots)
α_{mac}	angle of attack referenced to the wing mean aerodynamic chord, deg
α_p	angle of attack referenced to the probe centerline, deg
Δ	correction or error in quantity following

Subscripts:

i	indicated value
ic	corrected for instrument error
icl	corrected for instrument error and pressure lag

S_1	measured from static-pressure source S_1
S_2	measured from static-pressure source S_2
S_3	measured from static-pressure source S_3
I	measured by System I
II	measured by System II

AIRCRAFT INSTRUMENTATION

Probes

A photograph of the YF-12 pitot-static probe with a flow direction probe attached is shown in figure 1. A conventional YF-12 pitot-static probe has two sets of static-pressure orifices designed to compensate for static source position error at transonic

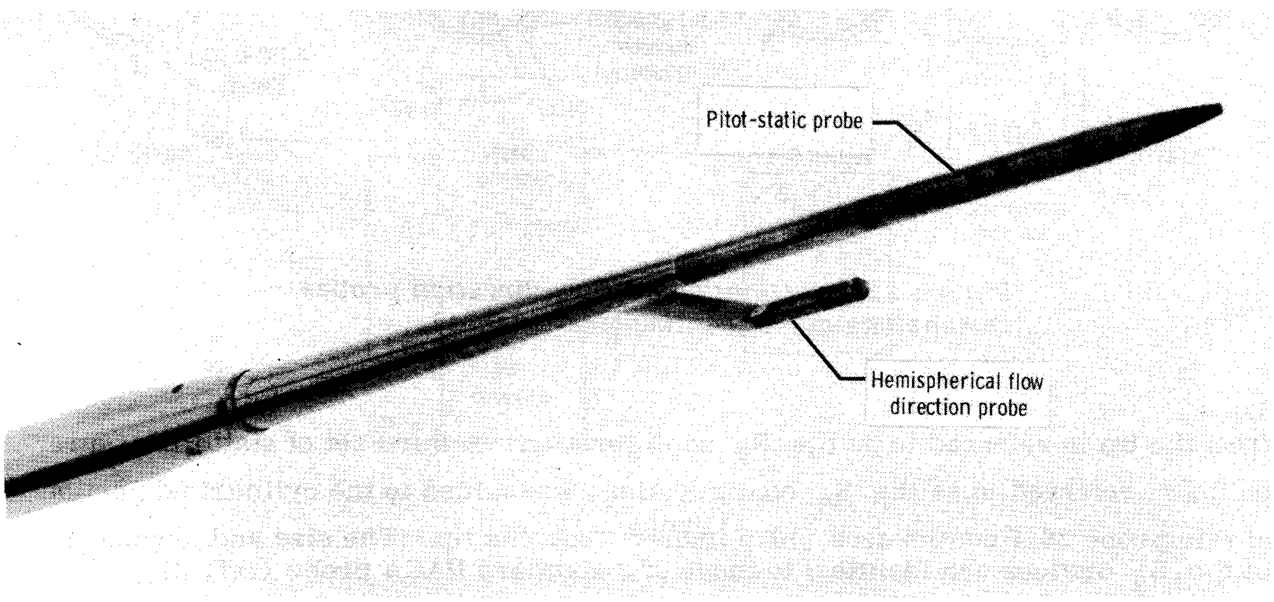


Figure 1. Pitot-static probe with attached hemispherical flow direction probe. *E-25920*

speeds. Both sets of four orifices are on the contoured surface near the forward end of the probe (fig. 2). The set 7.05 centimeters (2.78 inches) from the tip of the probe is referred to as the S_1 configuration, and the set 7.82 centimeters (3.08 inches)

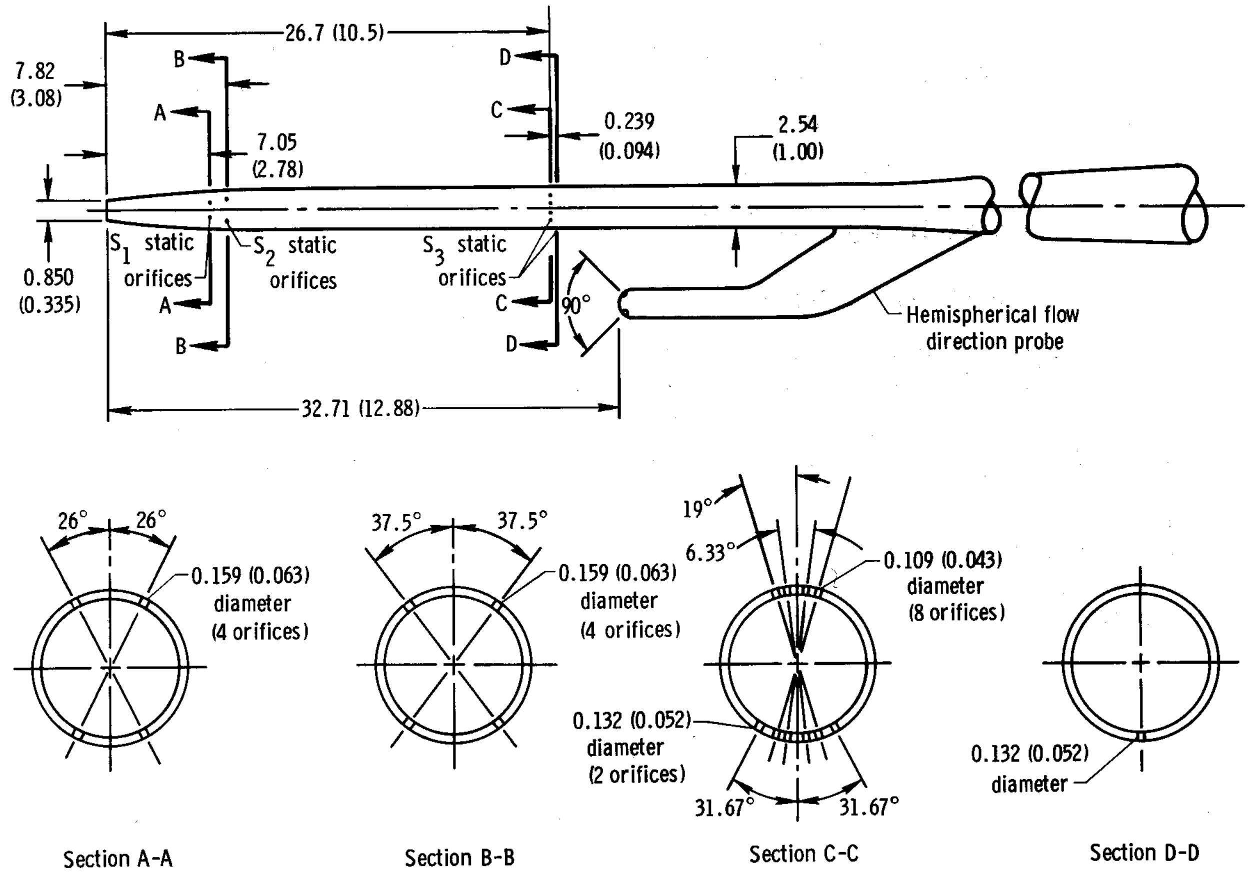


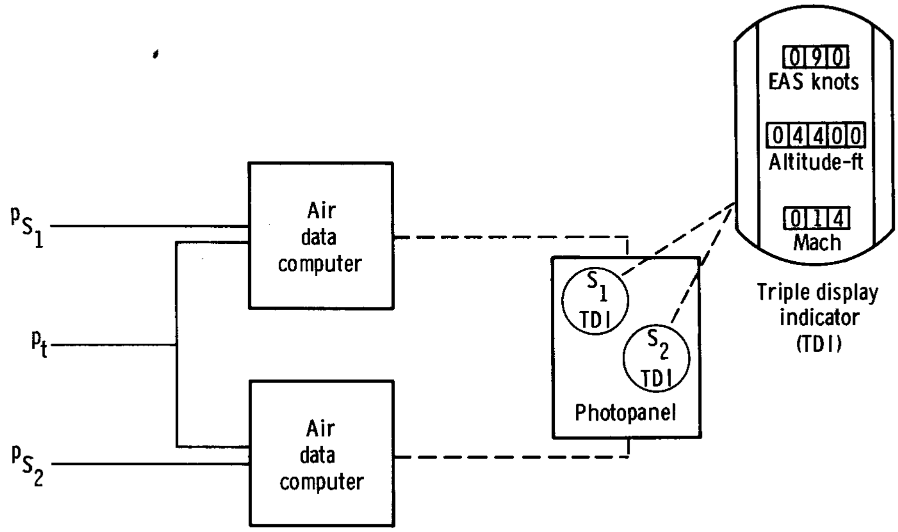
Figure 2. Pitot-static and flow direction probes.
Dimensions are in centimeters (inches).

from the tip is referred to as the S_2 configuration. A third set of static-pressure orifices, referred to as the S_3 configuration, was added to the cylindrical portion of this probe 26.7 centimeters (10.5 inches) from the tip. The size and arrangement of the S_3 orifices are identical to those of a standard NACA probe (ref. 3).

The probe attached to the pitot-static probe (fig. 1) has a hemispherical flow direction sensor. This device, which senses differential pressures from two sets of dual orifices, is used for the determination of angle of attack and sideslip (ref. 4). A wind-tunnel calibration, which allows flow angles to be determined in terms of Mach number and dynamic pressure, is used for data reduction. Reference 5 states that the accuracy of this system for the YF-12 airplane is within 0.25° except in the transonic region, where the accuracy of the measurements is within approximately 0.5°. Both this probe and the pitot-static probe were drooped 3.0° with respect to the mean wing chord.

System I

Figure 3 shows a schematic of the two pitot-static recording systems that are discussed and compared in this paper. In System I, measurements from only the S_1 and S_2 static orifices were used. There were two identical air data computers, each of which was equipped with an absolute transducer for sensing static pressure and a differential transducer for sensing the differential between the pitot and static pressures. Both computers used the pitot pressure sensed at the common pressure port. Mach number, pressure altitude, and equivalent airspeed acquired from the air data computer that was used for the S_2 measurements were displayed digitally on triple display indicators in both cockpits of the aircraft. The other air data computer was specially installed to ascertain the static source position error of the S_1 static-pressure orifices, which were used to acquire data for a conventional, backup airspeed-altitude display. The outputs from the air data computers were also displayed on a photopanel that incorporated two triple display indicators (fig. 3 and ref. 6).



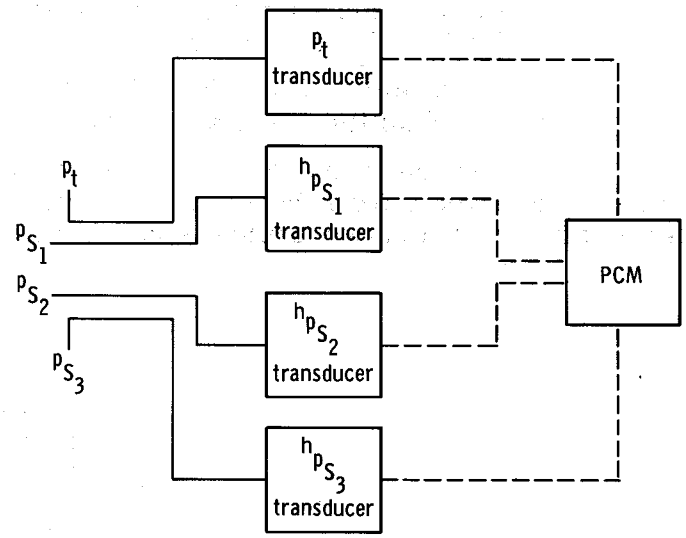
(a) System I.

Figure 3. Pitot-static recording system.

A mechanical cam in each air data computer corrected the outputs of pitot pressure to pitot-static differential pressure; therefore, it is referred to as a static error compensation (SEC) cam. The cam corrections for both air data computers were identical, and were designed to sense pressures from the S_2 static-pressure source.

System II

In System II, static pressures from all three sources—S_1, S_2, and S_3—were measured, but the measurements were the direct output of pressure altitude transducers (of the force balance type) instead of the output of air data computers. These static pressures and the pitot pressure, which was also sensed by a transducer, were recorded on a pulse code modulation (PCM) flight tape.



(b) System II.

Figure 3. Concluded.

The design of System II gave it several advantages over System I. First, although the S_3 source did not compensate for transonic position error, the source was relatively insensitive to angles of attack up to 10° (ref. 3). Second, the pitot and static pressures (pressure altitude) were measured directly. Third, the transducers were in the nose section of the aircraft, which permitted the pneumatic lines to be 5.3 meters (17.3 feet) shorter than in System I; this reduced pressure lag. And last, data processing from PCM recordings is automatic.

CALIBRATION PROCEDURES

Ground

Routine laboratory calibrations were performed to determine the systematic instrument errors of the System II pressure transducers. Two types of pressure manometers were used for this purpose. One of these manometers is accurate within

1.69 N/m^2 (0.00025 psi) plus 0.004 percent of reading, and the other is accurate within 6.75 N/m^2 (0.00100 psi) plus 0.002 percent of reading. Table 1 lists estimates of the accuracies of the System II transducers based on these calibrations and flight experience. The table also includes the resolutions of the recorded measurements.

TABLE 1.— SYSTEM II TRANSDUCER ACCURACIES AND RECORDING RESOLUTIONS

	Accuracy with calibration	Recording resolution
h_p, m (ft)	±20 (±66)	3.4 (11)
p_t, N/m^2 (lb/in^2)	±69 (±0.01)	17 (0.0025)

Although the specification accuracies of the air data computer are generally satisfactory for pilot displays and the aircraft control systems (table 2), they are larger than is desirable for flight reference data. Therefore, special laboratory

TABLE 2.— AIR DATA COMPUTER TOLERANCES AND TRIPLE DISPLAY INDICATOR READING RESOLUTIONS

	Air data computer specification accuracy	Triple display indicator digital increment	Triple display indicator reading resolution
M	±0.02	0.01	0.0025
h_p, m (ft)	±113 (±370)	15 (50)	5 (15)
V_e, m/sec (knots)	±3.2 (±6.3)	0.5 (1)	0.13 (0.25)

calibrations were performed on four air data computer-triple display indicator (ADC-TDI) units that were to be used for flight position error calibrations. Two ADC-TDI units for S_1 measurements and two units for S_2 measurements were calibrated in the laboratory simultaneously. Known pressure values were applied to the pitot and static ports of the air data computer. Static pressure was controlled and measured by the more accurate of the manometers. The pitot pressure, which does not have to be measured as accurately as static pressure, was set by using a pressure ratio gage referenced to the static-pressure input. Different pressures were applied to the static port to permit various values of pressure altitude (as defined in ref. 7) to be derived. Since Mach number is calculated from the ratio of pitot pressure to static pressure, a number of different pressures were also applied to the pitot port to allow several Mach numbers to be determined for each pressure altitude. Equivalent airspeed was calculated from Mach number and pressure altitude for each calibration point. The resulting values of those three quantities were then compared with the corresponding values from the two triple display indicators to determine the instrument corrections for both (S_1 and S_2) ADC-TDI combinations. In total, 272 calibration points distributed throughout the performance envelope of the aircraft were acquired. These calibration points were used to define the instrument correction curves presented in this paper.

Pressure lag calibrations were performed on the aircraft during hangar tests by inputting known pressures at different rates to the nose boom pitot- and static-pressure ports.

Flight Calibrations

The three static-pressure sources were calibrated in flight for position errors at low angles of attack (α_p = -1° to 2°) by using precision ground-based radars and upper air rawinsonde measurements for supersonic flight and by pacer measurements for subsonic flight.

Pushover-pullup maneuvers were performed to determine the effects of angle of attack on the S_1 and S_2 measurements. The static source pressures from those tests were corrected for position error, as defined from the low-angle-of-attack calibration, and pressure lag. The resulting S_1 and S_2 values were then compared with the S_3 values to define the effects of angle of attack on the S_1 and S_2 position errors. It was assumed that the effects of angle of attack on the S_3 measurements were insignificant.

An analytical error analysis indicates that the position error was measured with an accuracy of ±0.005 at a Mach number of 0.6 and ±0.017 at a Mach number of 3.0 when System I instrumentation was used (table 3). A comparison shows that at Mach numbers between 2.0 and 3.0 System II was twice as accurate.

TABLE 3.— ESTIMATED POSITION ERROR MACH NUMBER ACCURACIES

$\left[\alpha_p = -1° \text{ to } 2°\right]$

M	System I	System II
0.6	±0.005	±0.003
0.96	±0.012	±0.008
2.0	±0.010	±0.005
3.0	±0.017	±0.009

RESULTS AND DISCUSSION

Instrument Calibrations

System I calibration curves. — Figures 4 to 7 present instrument corrections for a typical ADC-TDI combination. Shown in figure 4 is the Mach number calibration for increasing total pressure. The different symbols represent various pressure altitudes, and the curves are isopleths of pressure altitude as interpreted from the data. The values of the pressure altitudes, which are not necessary for this discussion, are omitted from the curves and data points because of their security classification. The instrument correction for any given indicated Mach number varies considerably, but it is possible to make corrections in terms of pressure altitude. This dependence on pressure altitude is believed to be the result of error in the static-pressure transducer in the air data computer. Not all ADC-TDI units exhibited a well-defined altitude dependence. It was also found that a hysteresis error, which amounted to as much as 0.006 in Mach number and depended on whether pitot pressure increased or decreased, resulted from this variation.

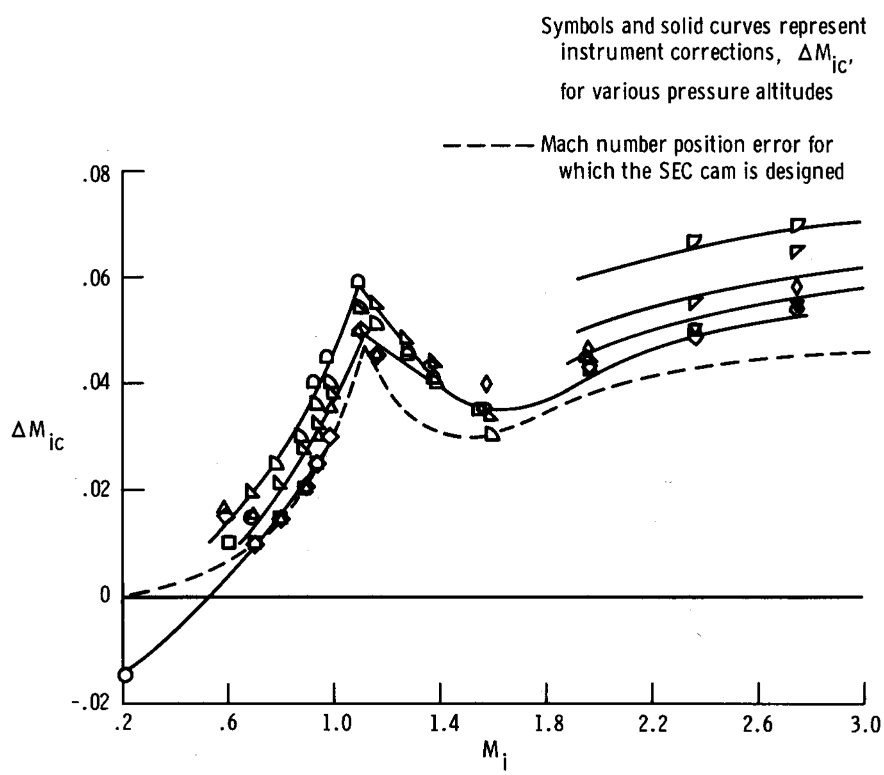


Figure 4. Typical Mach number instrument calibration of an ADC-TDI combination. Increasing p_t.

The values of the instrument corrections are large because of the negative Mach number corrections applied by the SEC cam. Included in figure 4 is the Mach number position error for which the cam is designed. The difference between the calibration curves and the cam curve represents true instrument corrections. Part of the instrument corrections are due to systematic error in the SEC cam (the cam cannot be expected to provide exactly the correction intended), and the remainder is due to the other systematic errors in the ADC-TDI unit. For convenience and ease of interpretation, the intended SEC corrections were ignored and the solid curves in figure 4 were used for instrument corrections when static-pressure position errors were determined from flight measurements. In this way, the effect of the cam was treated as just another source of error in the instrumentation system.

Figure 5 presents the pressure altitude instrument correction for a particular pressure altitude as a function of M_i. Hysteresis is evident at all except subsonic Mach numbers. Final pressure altitude instrument correction curves like those in figure 6 were derived by cross-plotting data like those in figure 5. Because the SEC cam is designed to provide a constant pressure altitude correction for all altitudes shown in figure 6 above 11 kilometers (36,200 feet) for any particular M_i, the variation of correction shown in this figure above 11 kilometers (36,200 feet) is not intended and thus truly reflects instrument error.

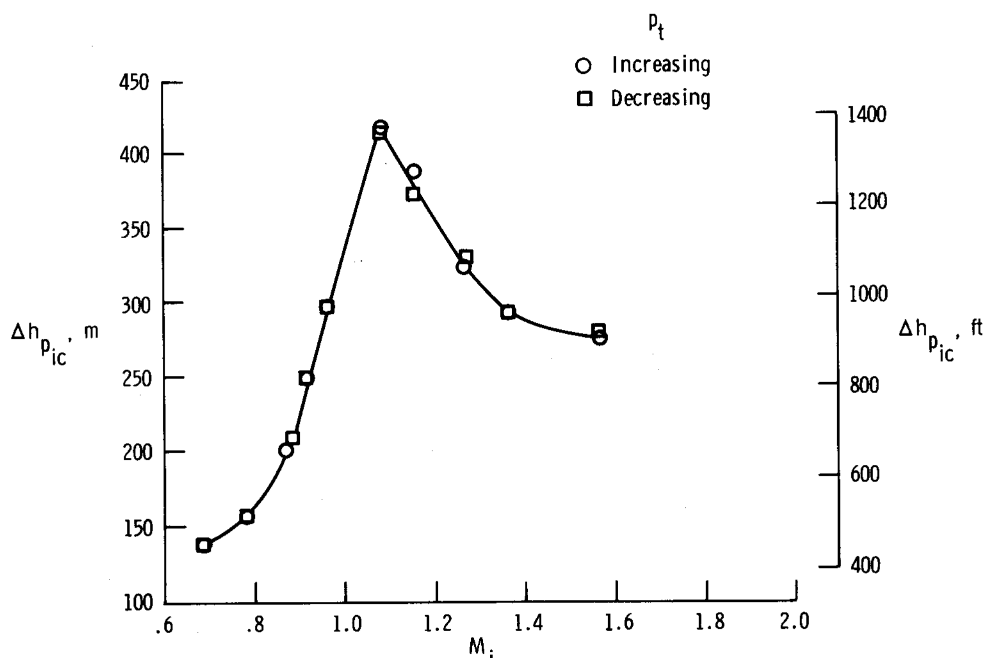


Figure 5. Typical pressure altitude instrument correction for an ADC-TDI combination. Constant h_p.

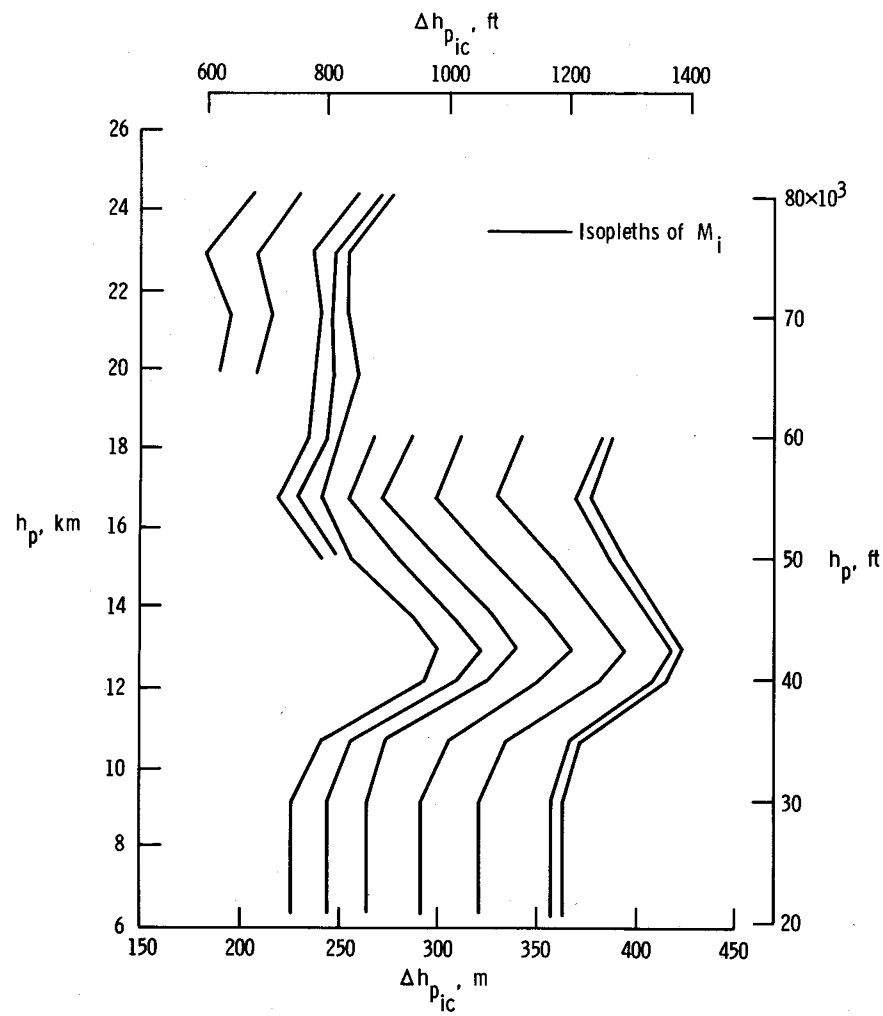
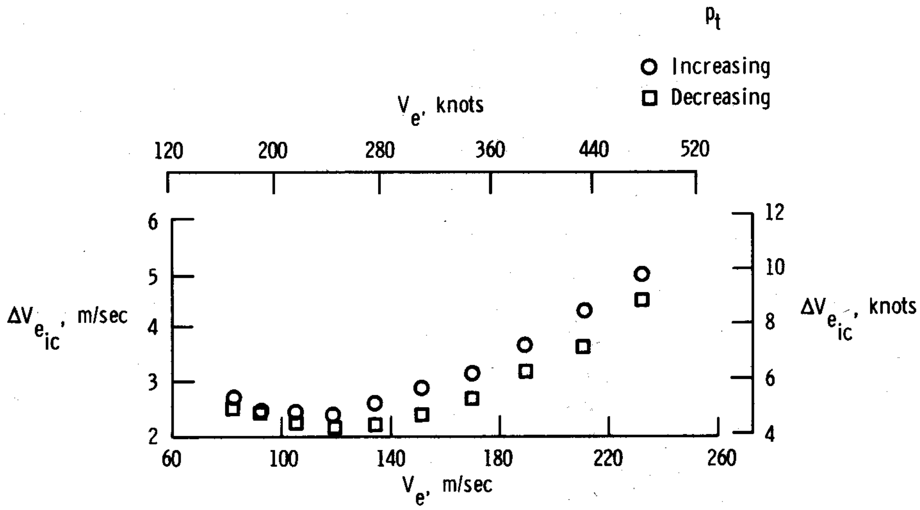
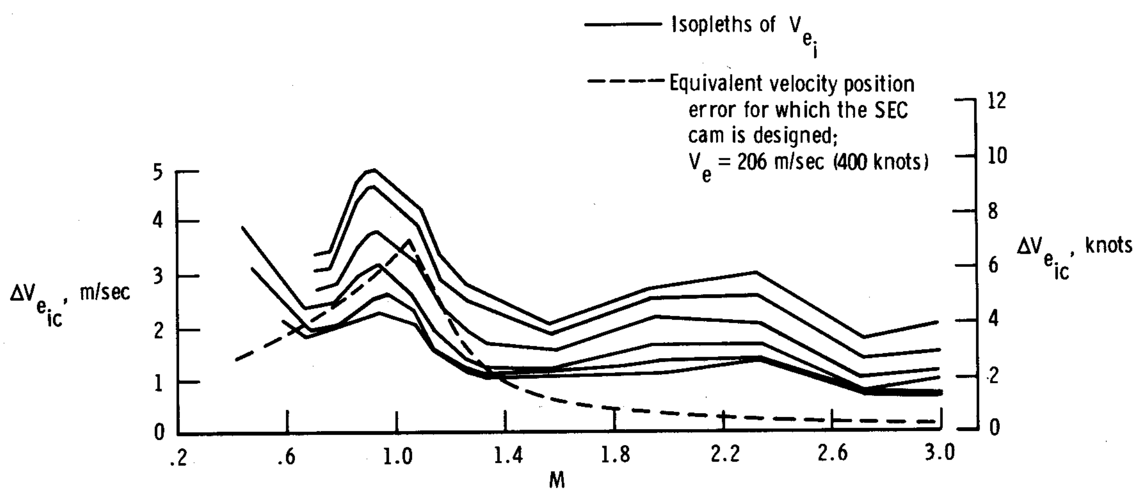


Figure 6. Typical supersonic pressure altitude instrument correction for an ADC-TDI combination.

Shown in figure 7(a) are instrument corrections for equivalent airspeed at a particular indicated Mach number for both increasing and decreasing pitot pressure. Cross-plotting all available data resulted in final calibration curves like those in figure 7(b). The dashed curve is the equivalent velocity position error at 206 meters per second (400 knots) for which the SEC cam is designed. Since one of the calibration curves (solid lines) is also for 206 meters per second (400 knots), the instrument errors are relatively significant.



(a) Typical data for a particular Mach number.



(b) Typical calibration. Increasing p_t.

Figure 7. Typical supersonic equivalent airspeed instrument calibration data and final calibration for an ADC-TDI combination.

System I instrument correction procedure.— Inconsistency can arise if such instrument calibration curves as those shown in figures 4 to 7 are used. That is, if all three triple display indicator quantities—Mach number, pressure altitude, and equivalent airspeed—for a given data point are corrected for instrument error, the three corrected values may not be in the proper mathematical relationship to each other. To avoid such inconsistencies, the corrected values of two of the quantities were accepted and the third was calculated. The selection process depended on which values resulted in the best expected accuracy in Mach number and pressure altitude. Since pressure altitude depended only on static pressure, the corrected triple display indicator value of this quantity was probably more accurate than the value that could be derived from corrected triple display indicator values of Mach number and equivalent airspeed, both of which are dependent on pitot pressure as well as static pressure. For the ADC-TDI calibration under discussion, analysis showed that when indicated Mach number was greater than 1.6, the best accuracy was achieved by computing equivalent airspeed from the instrument-corrected pressure altitude and Mach number. However, when indicated Mach number was less than 1.6, best accuracy was achieved by computing Mach number from instrument-corrected pressure altitude and equivalent airspeed. This is shown in figure 8, where the accuracy of Mach number is plotted as a function of indicated Mach number. When all four calibrated ADC-TDI units were considered, an indicated Mach number of 1.5 was selected as the changeover point for the procedure.

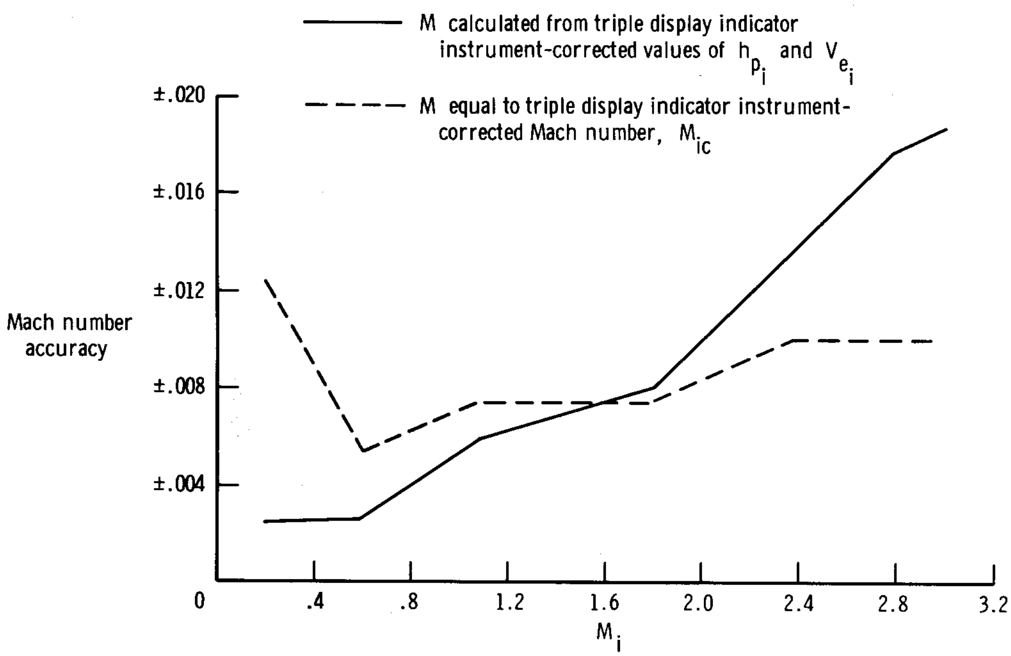


Figure 8. Calibration accuracies of Mach number as obtained directly from a triple display indicator and computed from instrument-corrected values of h_{p_i} *and* V_{e_i}.

This discussion illustrates the difficulty of calibrating and interpreting data from an air data computer, especially one that incorporates a mechanical SEC cam. Certainly, the direct measurement of pitot and static pressure (or pressure altitude) is a more convenient way to obtain accurate free-stream pressure-related air data quantities.

Check of instrument corrections in flight.— Pressure altitude measurements from the S_1 source and System I (which used an ADC-TDI unit) are compared with pressure altitude measurements from the S_3 source and System II (which used a pressure altitude transducer) in figure 9. All the data in the figure are corrected for instrument error. The data were selected for a period of near-level flight to

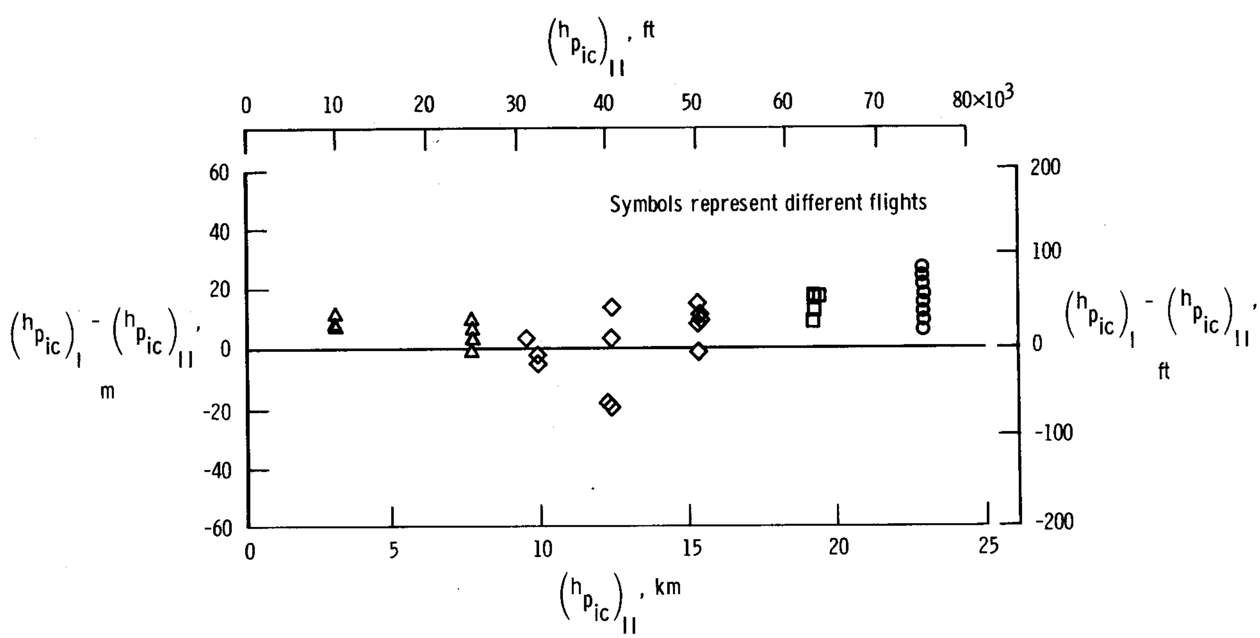
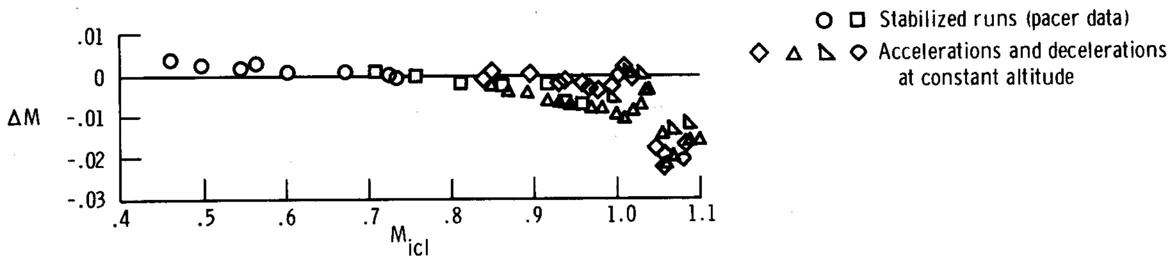


Figure 9. Difference between pressure altitudes measured in flight by a System II pressure altitude transducer and by System I with an ADC-TDI combination.

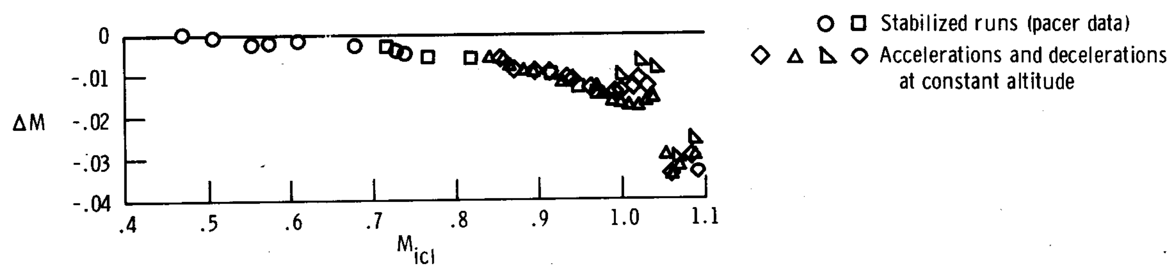
minimize the effects of pressure lag differences in the instrumentation. As the figure shows, the pressure altitude differences were less than 25 meters (82 feet) for the four flights. The maximum difference is only 5 meters (16 feet) greater than the estimated accuracy of the System II transducer (see table 1). Therefore, reasonably accurate pressure altitude measurements were obtained with System I. A System II pressure transducer for the measurement of pitot pressure was not flown at the same time as an ADC-TDI unit, so measurements of Mach number and equivalent airspeed cannot be compared for the verification of the calibration of other instrumentation. However, as indicated by table 3, an error analysis of the results of the instrument calibrations indicates that System II is more accurate than System I.

Comparison of Static Source Position Errors

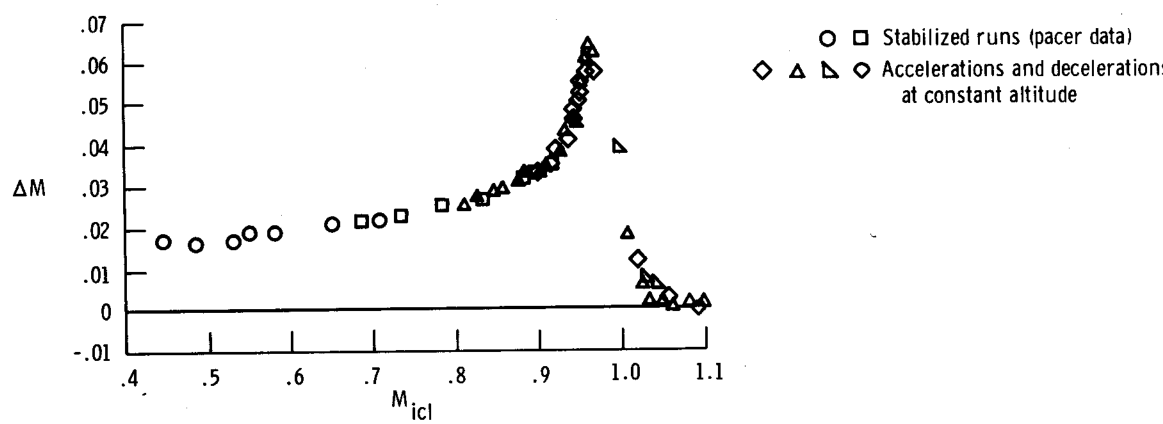
Effects of Mach number. — Flight data representing subsonic and transonic corrections for position error for nose boom angles of attack between -1° and 2° are presented in figure 10. These data were derived from System II instrumentation.



(a) S_1.



(b) S_2.



(c) S_3.

Figure 10. Static source position error calibrations for the compensated and uncompensated static-pressure systems. α_p = -1° to 2°.

Some data are from calibration runs at stabilized flight conditions during which the pacer calibration technique was used, and the other data are from accelerating or decelerating calibration runs. As expected, the effects of compressibility and the aircraft bow shock are more pronounced for the uncompensated source, S_3, than they are for the two compensated sources. However, near to and in the Mach number range where the bow shock passage occurs, the corrections for the position error are better defined and more repeatable for the S_3 source than they are for the compensated sources.

Figure 11 shows final calibration correction curves for the entire Mach number range up to an M_{icl} of approximately 3.0. Included in the figure is the programed

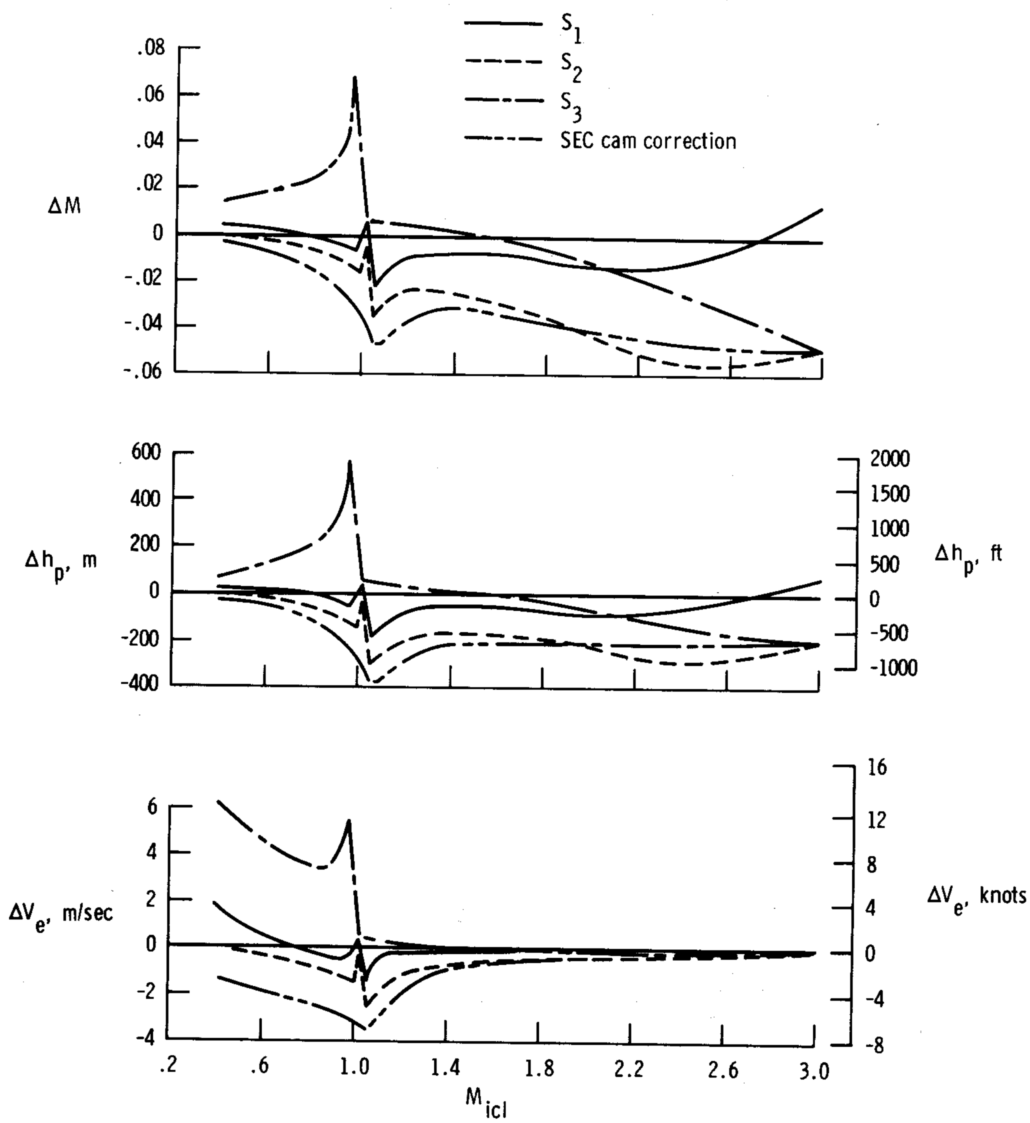


Figure 11. Comparison of static source position error curves. V_e = 206 m/sec (400 knots); α_p = -1° to 2°.

Mach number cam correction, which should be compared with the S_2 static-pressure position error correction. The differences between the S_2 position error curve and the SEC cam curve near the shock jump region, although small, can significantly affect the pilot's ability to maintain a given altitude, as may be required occasionally for a test maneuver. That is, the SEC cam does not correct for position error perfectly, so erratic behavior, including jumps in the pilot's triple display indicator pressure altitude, results. This may cause the pilot to make excessive control inputs, which can result in larger altitude excursions from the assigned altitude than would occur because of SEC cam error alone.

The compensated static source configurations, S_1 and S_2, were designed to minimize error at transonic speeds, but it is also of interest to compare their corrections for position error with those of the uncompensated source, S_3, at supersonic speeds. As figure 11 shows, S_3 position errors are smaller than S_1 and S_2 errors up to $M_{icl} = 2.0$. From this value to $M_{icl} = 3.0$, the S_3 errors are between those of the other two sources. The S_1 and S_2 corrections either remain nearly constant or decrease with M_{icl} from 1.3 to 2.0. This variation at supersonic Mach numbers is similar to the behavior of position error corrections required for aft compensating static-pressure sources as well as from uncompensated sources (ref. 8). However, at higher Mach numbers, the slopes of the correction curves reverse. In figure 11, this reversal occurs at $M_{icl} = 2.2$ and $M_{icl} = 2.5$ for the S_1 and S_2 sources, respectively.

Effects of angle of attack on position error. — Figure 12 presents data for a typical pushover-pullup maneuver that was flown to determine the effects of angle of attack on the position errors of the S_1 and S_2 static-pressure sources. This particular maneuver provided a variation of angle of attack of more than 6°, during which M_{icl} remained near 2.5. While the pullup is being executed and angle of attack increases, the S_1 and S_2 values of $h_{p_{icl}}$ increase rapidly compared with the S_3 values. When the pushover is executed and angle of attack decreases, the S_1 and S_2 values of $h_{p_{icl}}$ decrease abruptly, even though actual altitude is still increasing. Obviously, the S_1 and S_2 measurements are sensitive to angle of attack at the test Mach number (near 2.5). The S_3 measurements are not sensitive to angle of attack. The erratic behavior of the pressure altitude indications from the compensated sources shows up in pilot displays, which is probably why pilots prefer inertial displays of altitude and altitude rate for performing some maneuvers with the test aircraft.

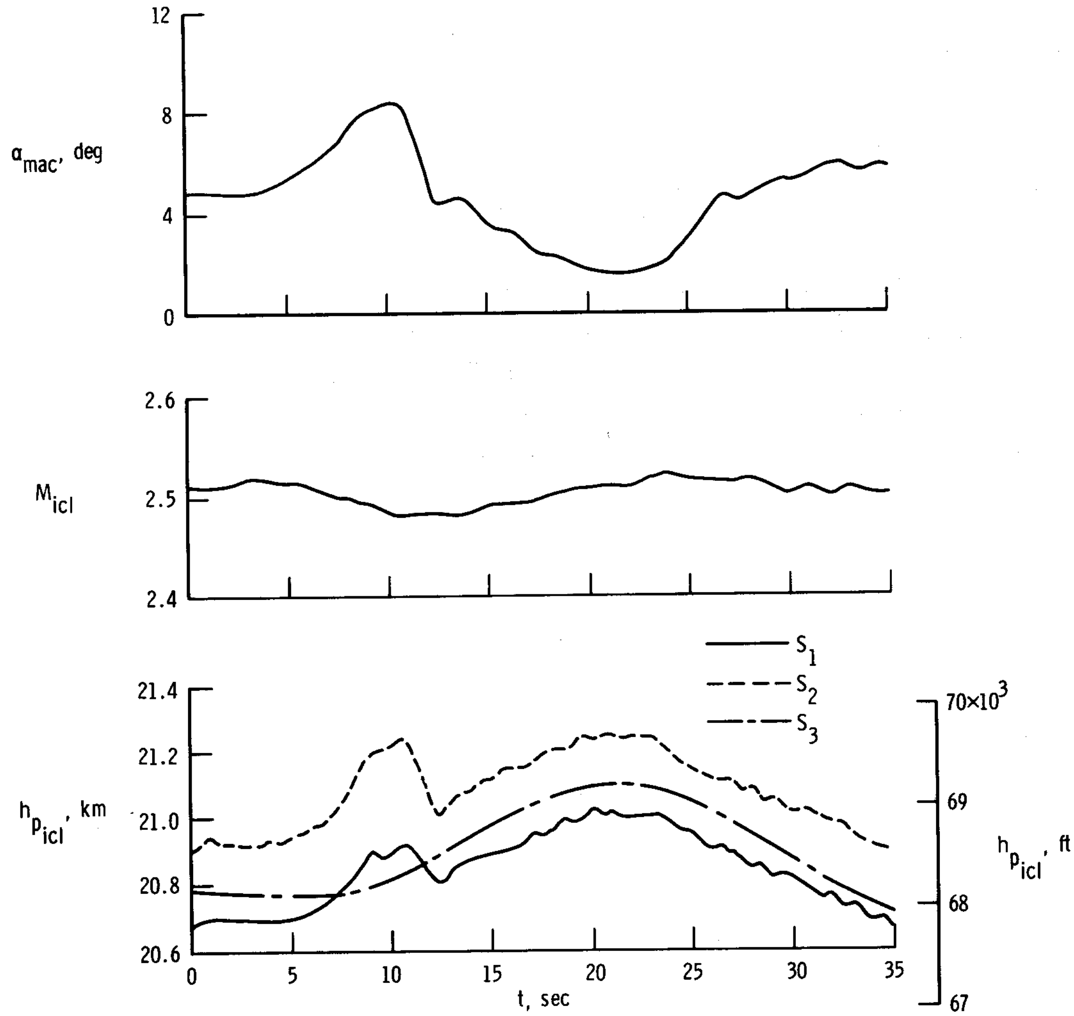
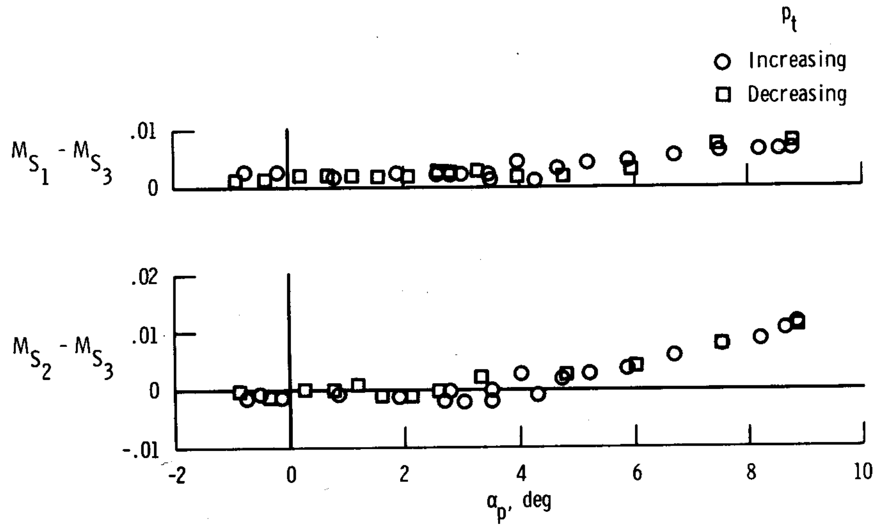
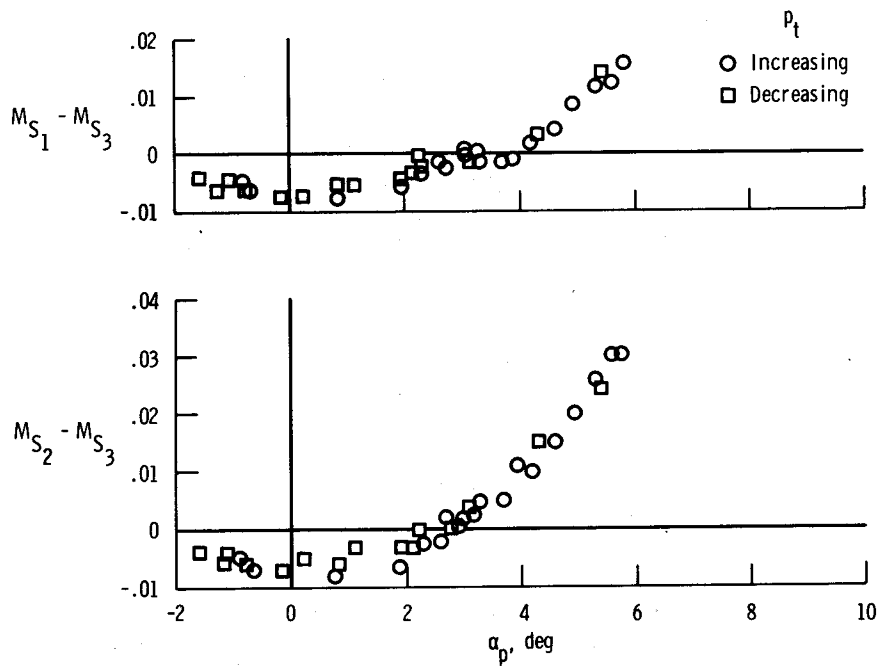


Figure 12. Mach number, angle of attack, and pressure altitude during a typical pushover-pullup maneuver.

The effects of angle of attack on the static-pressure measurements are clearly apparent in figure 13, which shows the differences $M_{S_1} - M_{S_3}$ and $M_{S_2} - M_{S_3}$ from various pushover-pullup maneuvers, including that in figure 12, plotted against probe angle of attack. The data for increasing and decreasing angles of attack are differentiated to reveal any effects of lag in the angle-of-attack measurements. Because of the symmetrical arrangement of the orifices for both compensated configurations (fig. 2), zero Mach number difference was expected at $\alpha_p = 0°$. However, as the figure shows, indicated Mach number differences are not always zero at this condition, probably because of inexact instrument error correction.

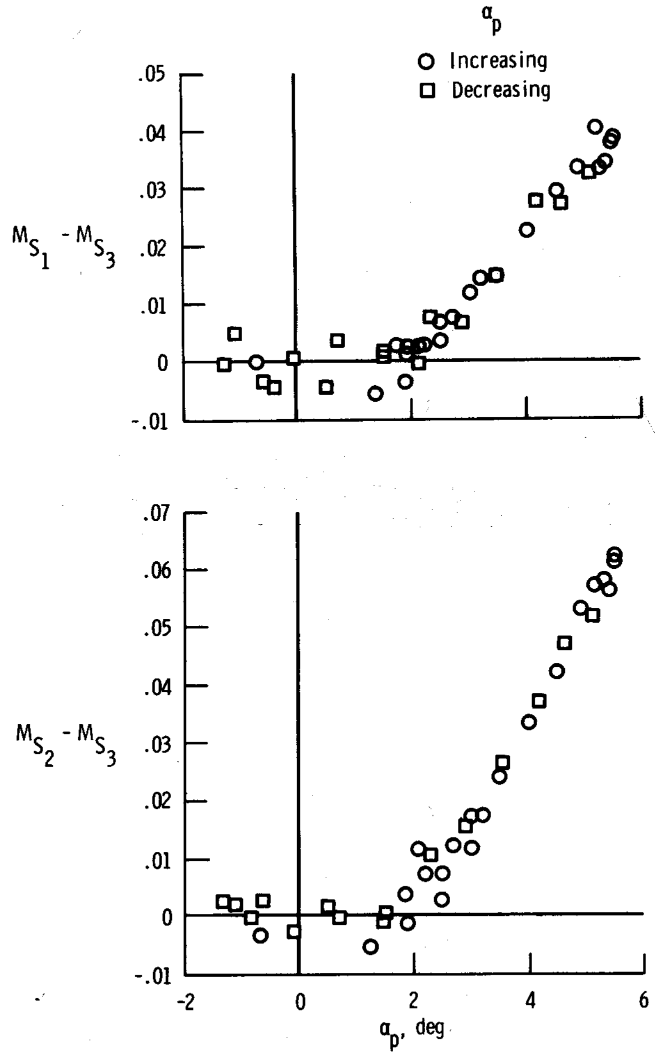


(a) $M \approx 0.95$.



(b) $M \approx 2.0$.

Figure 13. Typical differences in Mach number measurements between compensated and uncompensated static-pressure systems with variation in angle of attack.



(c) $M \approx 2.5$.

Figure 13. Concluded.

Fairings were made of the data in figure 13 as well as of data obtained from other pushover-pullup maneuvers and adjusted to pass through coordinate points (0,0). Points were read from these fairings in 1° increments and plotted against M_{icl} to determine constant angle-of-attack curves like those shown in figure 14. The M_{icl} values shown for the data in the figure represent flight run averages for each value of angle of attack.

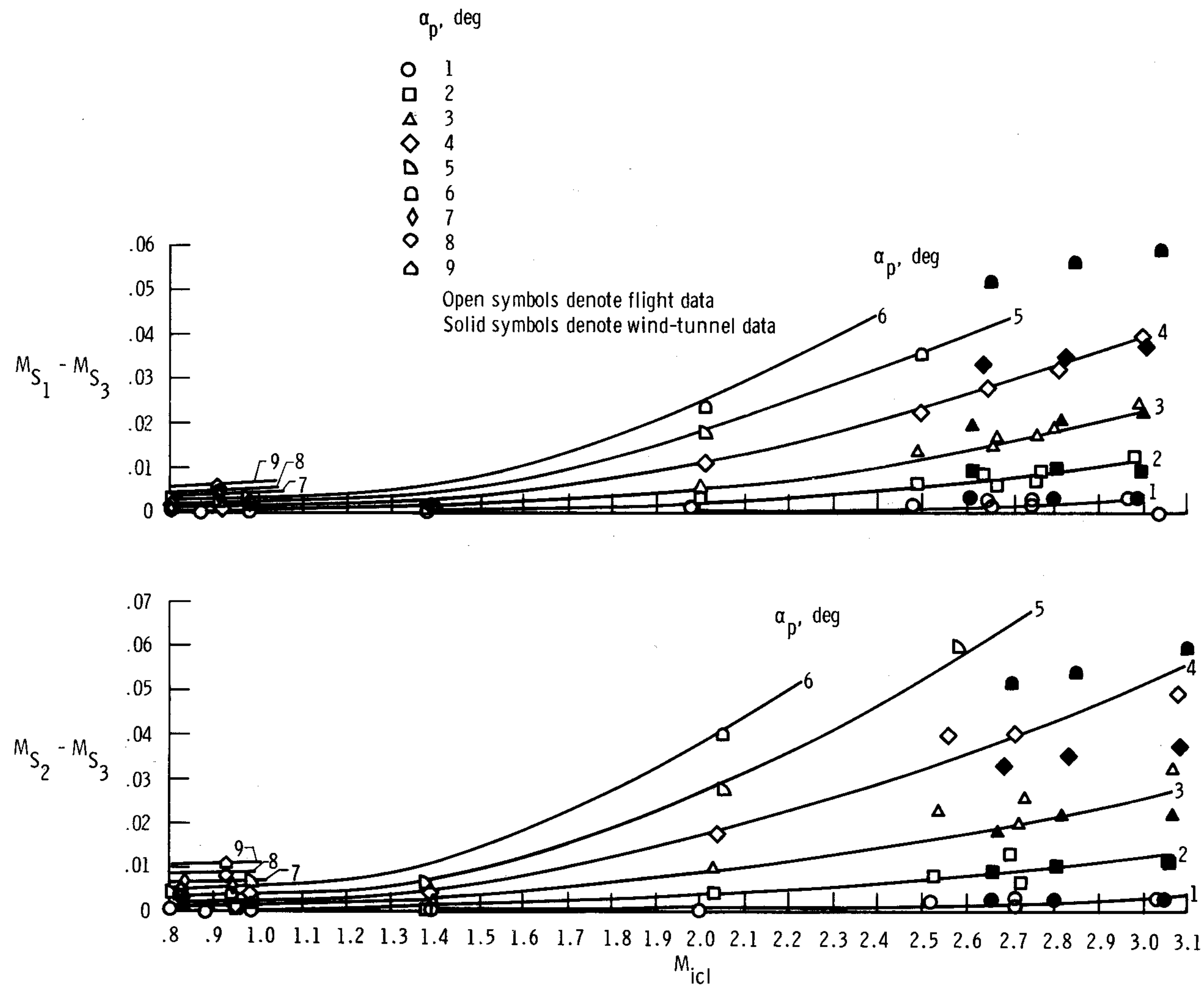


Figure 14. Static source position error calibrations of uncompensated static orifice configurations for angle of attack.

According to reference 3, errors due to angle of attack in S_3 Mach number measurements are generally within 0.005 for the range of the data shown in figure 14. Therefore, the Mach number differences in this figure are assumed to represent errors in the S_1 and S_2 measurements due to angle of attack.

In figure 14, the Mach number differences increase with angle of attack and at an increasing rate with Mach number, and S_2 errors are larger than the S_1 errors. For example, at an M_{icl} of 3.0 and a probe angle of attack of 4°, the resulting S_1 and S_2 Mach number differences are 0.04 and 0.05, respectively. This observation does not agree with unpublished wind-tunnel measurements that indicate no significant differences between the S_1 and S_2 measurements due to angle of attack. To be more specific, the wind-tunnel data for the S_1 source agree favorably with the flight data, but indicate only a slightly larger error for the S_2 source.

CONCLUDING REMARKS

A set of uncompensated static-pressure orifices on a modified YF-12 probe was a more accurate static-pressure-measuring configuration for air data recording than either of two sets of compensated static-pressure orifices. Whereas the uncompensated orifice configuration was relatively insensitive to angle of attack, at supersonic speeds the compensated configurations exhibited errors due to angle of attack that increased with both angle of attack and Mach number. Although the uncompensated static-pressure source exhibited larger position errors than the compensated static-pressure sources at transonic Mach numbers, the errors were better defined and more repeatable than those of the compensated sources.

Because the air data computer provides static error compensation, the uncompensated source, even with its large subsonic position errors, would be a more accurate source of air data for pilot display than either of the compensated sources.

Pitot-static measurements made on the YF-12 aircraft with air data computers that incorporated mechanical cam corrections for aircraft static-pressure position errors provided reference data that were inaccurate when compared with similar measurements made by using only pressure transducers. Although a system that incorporates such corrections is adequate for pilot display and aircraft control systems that depend on air data measurements, it is undesirable for reference measurements because of the difficulty of defining the relationship between the cam and the instrument corrections so that the true static source position error can be ascertained.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., September 17, 1974

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